Implications of the Visible and X-Ray Counterparts to GRB970228

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The gamma-ray burst source GRB970228[1,2] has been observed after a delay of 8–12 hours in X-rays[3] and after one day in visible and near infrared light[4]. This marks the first detection of emission at lower frequencies following the gamma-ray observation of a GRB and the first detection of any visible counterpart to a GRB. We consider possible delayed visible and X-ray emission mechanisms, and conclude that the intrinsic gamma-ray activity continued at a much reduced intensity for at least a day. There are hints of such continued activity in other GRB, and future observations can decide if this is true of GRB in general. The observed multi-band spectrum of GRB970228 agrees with the predictions of relativistic shock theory when the flux is integrated over a time longer than that required for a radiating electron to lose its energy.

Several mechanisms for the continuing X-ray emission of GRB970228 should be considered. The relativistic particles required to explain a GRB will collide with a surrounding dilute medium, a process which has been suggested[5] as the source of the gamma-ray emission itself. Simple analytic models of such external shocks which follow the degradation of the energy of the particles and fields lead to a predicted time scale of emission $\propto \nu_{obs}^{-5/12}$, where $\nu_{obs}$ is the frequency of observation[6]. Similarly, a simple model[7] in which relativistic electrons radiate their energy in a constant magnetic field predicts a time scale $\propto \nu_{obs}^{-1/2}$. These classes of models may be excluded because the observed duration of X-ray emission[3] is roughly 1000 times the reported gamma-ray duration[1], despite a ratio in $\nu_{obs}$ of only $\sim 50$. Another alternative model of the X-ray emission, thermal bremsstrahlung (as in a supernova remnant), may also be excluded because the required power $\sim 10^{45}$ erg/s (at

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cosmological redshift $z = 0.498$[8,9]) would require an unachievable particle density $> 10^{10}$ $\mathrm{cm}^{-3}$ even if the maximum plausible mass of 1 $M_\odot$ is radiating.

Instead, we suggest that the observed brief intense gamma-ray emission of a GRB is only the tip of an iceberg; it emits gamma-rays at a much lower level for time of order a day following (and perhaps preceding) the intense outburst. GRB detectors necessarily have high backgrounds because they must have very broad angular acceptance; these high backgrounds, lack of angular discrimination and necessarily short integration times imply high thresholds for detected flux, making the continuing weak gamma-ray emission difficult to observe by the burst detector. The X-ray and visible radiation is then produced by the same mechanism as the gamma rays, simultaneously with their continuing emission.

There is independent evidence for continuing gamma-ray activity in GRB, with durations longer than the usual values $< 1000$ s[10]. GRB940217 was observed[11] to emit energetic gamma-rays over a duration of $\approx 5000$ seconds. The group of four GRB observed[12,13] October 27–29, 1996, apparently from a common source, may equally well be described as repeating bursts or as a single burst lasting two days with brief periods of high intensity amidst a much longer period of undetectably low intensity. The occasional observation of "precursors" some time before the peak emission of a GRB[14] may also indicate a longer period of weak activity.

The hypothesis that many GRB last a day or more is consistent with the demonstration[15] that the observed complex time structure of GRB on scales of seconds must be attributed to variations in the power of their energy source. Without a better understanding of this central engine, durations of a day are no less plausible than durations of tens of seconds.

Our suggestion that the X-ray and visible emission of GRB970228 was the consequence of continuing weak gamma-ray activity predicts that this gamma-ray emission should be observable in similar bursts by suitable instruments. It also leads to a specific prediction for its spectrum, which may be roughly tested with the data at hand. The instantaneous

spectrum of a relativistic shock is predicted[16,17] to be $F_\nu \propto \nu^{1/3}$. The spectrum integrated over the radiative decay of the electrons' energy is predicted[18] to be $F_\nu \propto \nu^{-1/2}$. Observations during the brief phases of GRB during which BATSE obtained data have shown soft gamma-ray spectra between these limits, with $F_\nu \propto \nu^{-1/2}$ found when the data are integrated over many subpulses, allowing time for shock-heated electrons to radiate their energy[18]. This prediction should be applicable to X-ray[3] and visible[4] data obtained over much longer periods of integration.

The data[2−4] from GRB970228 are collected in the Figure. The V and I band data were obtained[4] about one day after the observed GRB, and the X-ray data[3] were integrated over the period 8–12 hours after the GRB. Because these delays are similar, these data should be comparable. The solid line shows the predicted $F_\nu \propto \nu^{-1/2}$ slope, fitted (arbitrarily) to the V data point. The V, I, and X-ray data are all consistent with the predicted slope, confirming the hypothesis.

The only available gamma-ray data is that obtained[1,2] in the most intense 80 s of the GRB. This is not directly comparable to the visible, near infrared and X-ray fluxes obtained after longer delays, but it is possible to define an equivalent mean gamma-ray flux by dividing the gamma-ray fluence[2] by the estimated one day X-ray and visible decay time. This has been included in the Figure, and is also consistent with the predicted slope. The consistency of this equivalent mean gamma-ray flux with the extrapolated spectrum leads to the prediction that the actual mean flux is comparable to this value. It may be too late to test this prediction for GRB970228, but a similar analysis may be performed on future GRB.

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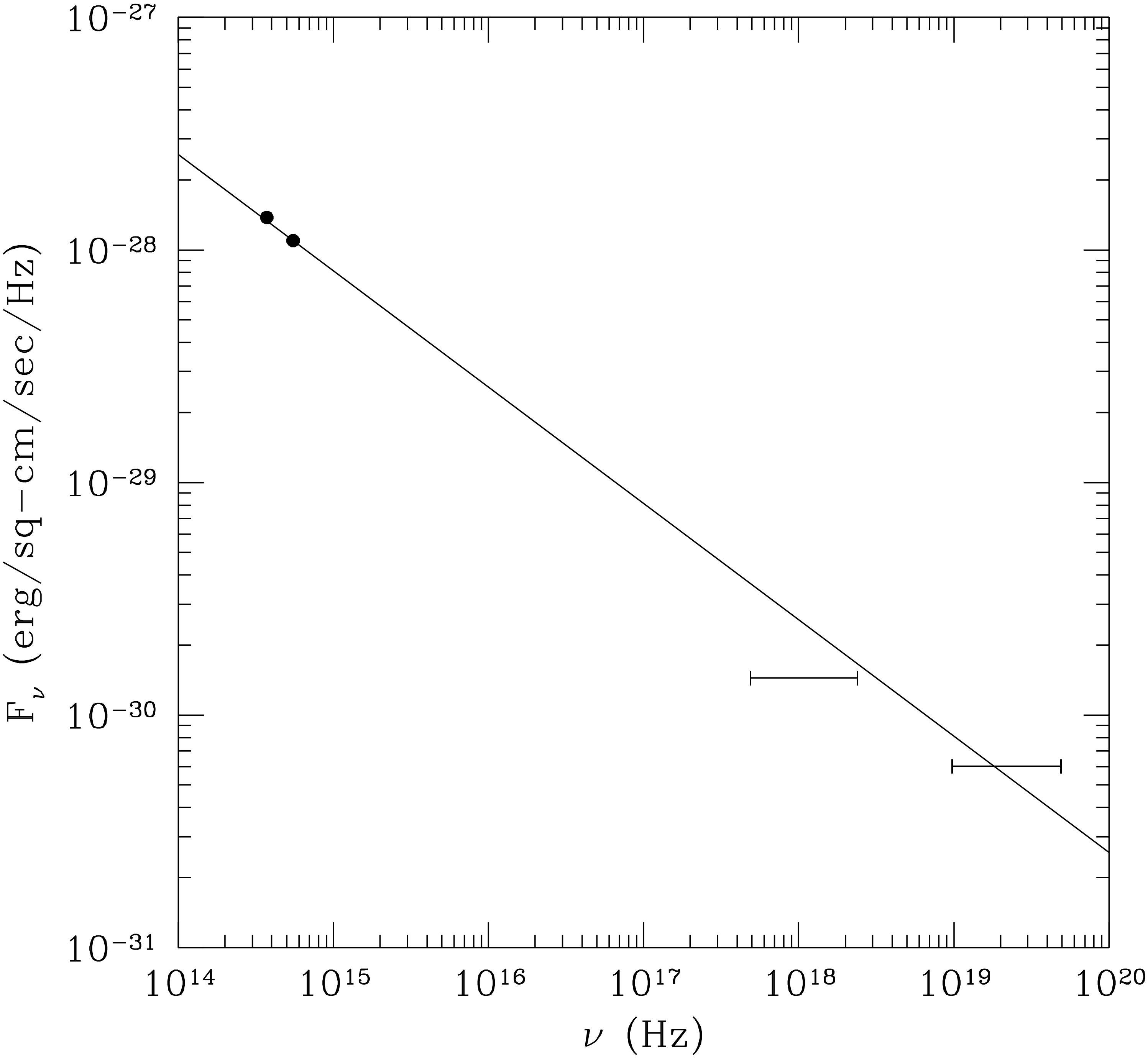
Figure Caption: Fluxes of GRB970228 in soft gamma-ray[2], X-ray[3], V[4] and I[4] bands. The soft gamma-ray flux is actually the fluence measured[2] in a 3.6 s spike in intensity, divided by the one day decay time roughly characteristic of the X-ray and visible fluxes. The straight line has the predicted $-1/2$ slope, normalized to the V band data.



$10^{-27}$
$10^{-28}$
$10^{-29}$
$10^{-30}$
$10^{-31}$
$F_\nu$ (erg/sq-cm/sec/Hz)
$10^{14}$
$10^{15}$
$10^{16}$
$10^{17}$
$10^{18}$
$10^{19}$
$10^{20}$
$\nu$ (Hz)